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16. ABSTRACT

A plant injury mathematical model, applied previously to acute and chronic leaf injury data, is used here to model National Crop Loss Assessment Network (NCLAN) data for 15 cultivars and to calculate species parameters from the cultivar analyses. Percent crop yield reduction is estimated as a function of a new parameter, the effective mean O_3 concentration: $m_e = [(\Sigma c_h^{-1/v})/n]^{-v}$, where c_h is the hourly average ambient O_3 concentration for each daytime hour (defined here as 9:00 A.M.-4:00 P.M., always standard time) of data available at an air sampling site for summer (defined here as June 1-August 31), n is the total number of such available hours, and v is an exposure time-concentration parameter, calculated here to be approximately -0.376. Crop yield reductions for seven plant species are estimated for each of the 1824 siteyears of 1981-1983 hourly O_3 concentration data available in the National Aerometric Data Bank (NADB). State-average O_3 parameters and estimated percent crop yield reductions are tabulated. Ambient O_3 concentrations reduced the total U.S. crop yield an estimated 5% for years 1981-1983.

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JOURNAL ARTICLE

An Air Quality Data Analysis System for Interrelating Effects, Standards, and Needed Source Reductions: Part 8. An Effective Mean O_3 Crop Reduction Mathematical Model

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A plant injury mathematical model, applied previously to acute and chronic leaf injury data, is used here to model National Crop Loss Assessment Network (NCLAN) data for 15 cultivars and to calculate species parameters from the cultivar analyses. Percent crop yield reduction is estimated as a function of a new parameter, the effective mean O_3 concentration: $m_e = [(\sum c_h^{-1/v})/n]^{-v}$, where c_h is the hourly average ambient O_3 concentration for each daytime hour (defined here as 9:00 A.M.–4:00 P.M., always standard time) of data available at an air sampling site for summer (defined here as June 1–August 31), n is the total number of such available hours, and v is an exposure time-concentration parameter, calculated here to be approximately −0.376. Crop yield reduction for soybean is calculated here as $z = 0.478 \ln (tm_e^{2.66}) - 0.42$, where z is the Gaussian transform of percent crop reduction, t is the hours of exposure (525 h is used here; 7 h/day for 75 days), and ln indicates that the natural logarithm is taken of the quantity within parentheses. Crop yield reductions for seven plant species are estimated with similar equations for each of the 1824 site-years of 1981–1983 hourly O_3 concentration data available in the National Aerometric Data Bank (NADB). County-average effective mean O_3 concentrations are indicated by shading on a U.S. map. State-average O_3 parameters and estimated percent crop yield reductions are tabulated. The National Ambient Air Quality Standard (NAAQS) for O_3 specifies that, on the average, the second highest daily maximum 1-h average O_3 concentration in a year shall not exceed 0.12 ppm. For years 1981–1983, 71% of the NADB sites recorded annual second highest daily maximum 1-h average O_3 concentrations below 0.125 ppm (for summer daytime hours). Ambient O_3 concentrations reduced the total U.S. crop yield an estimated 5% for years 1981–1983. (Summer, daytime, and all acronyms are always used herein as defined above.)

A lognormal[1] and some linear[2–6] plant injury mathematical models have expressed leaf injury as a function of an acute air pollutant exposure. In one study[7] of six plant species exposed to O_3, the percent variance in leaf injury left unexplained by the Heck-Tingey (H-T) model[6] was compared with that left unexplained by the Larsen-Heck (L-H) model.[1] The lognormal L-H model left an average of 14% of the variance unexplained. The linear H-T model left 3.5 times as much, 49%, unexplained. Thus, the lognormal model fit the acute leaf injury data better than did the linear model.

The L-H model also was fitted simultaneously[8] to both acute (exposures of up to a few hours) and chronic (exposures of up to 92 days for 6 h/day) O_3 leaf injury data. This acute-chronic application of the L-H model expressed leaf injury as a function of the logarithm of the summation of each hourly average O_3 concentration raised to an exponent. For Dare soybean for instance,

$$z = 0.4876 \ln (\sum c_h^{2.618}) - 0.0828 \quad (1)$$

where z is the Gaussian transform of percent leaf injury. This concentration-raised-to-an-exponent characteristic of the L-H model is used here to develop an effective mean O_3 concentration:

$$m_e = [(\sum c_h^{-1/v})/n]^{-v} \quad (2)$$

where c_h is the hourly average O_3 concentration for each available summer daytime hour of data at a site, n is the total number of such available hours, and v is an exposure time-concentration parameter.

Exposure time was held constant in each set of NCLAN experiments conducted thus far.[9,10] Plant injury studies in which both concentration and time are set at several different values are needed to estimate a value for the v parameter used in the above effective mean equation. An estimated v value is calculated here from leaf injury, growth suppression, and leaf dry weight reduction data, all of which give approximately the same v value, −0.376.

The remaining two parameters of the L-H model are calculated here for 15 cultivars by regressing NCLAN data. Species parameters are calculated from the cultivar parameters. The species parameters are then used to estimate percent crop reduction for seven plant species for each of the 1824 site-years of 1981–1983 ambient O_3 data in the NADB.

Average crop reductions estimated with the L-H model agree well with previous NCLAN linear[9] and Weibull[10] analyses, but the L-H model suggests that two air sampling sites with the same daytime arithmetic mean O_3 concentration (the parameter used in these other two approaches) may have quite different effective mean O_3 concentrations (Eq. 2) and estimated crop reductions.

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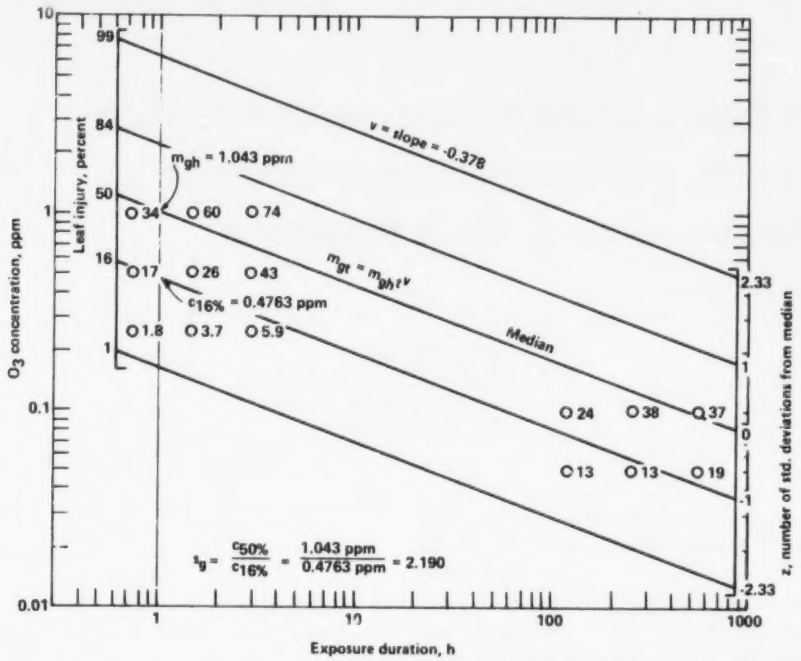

Figure 1. Percent leaf injury in Lee 68 and Dare soybeans exposed acutely (for 0.75, 1.5, or 3 h) and Dare soybean exposed chronically (for 120, 258, or 552 h) to O_3 (logarithmic plot).

Nomenclature

The nomenclature used here is essentially the same as that used previously.[1,8]

- c = O_3 concentration in ppm (Figures 1, 2)
- t = exposure time in h (logarithmic bottom axis of Figure 1)
- z = the number of standard deviations (right side of Figure 1) that a percent effect (left side of Figure 1) is located away from the median (50%); z is the Gaussian transform of the percent effect
- n = the number of hourly average O_3 concentrations available in a data set
- I = impact, a type of air pollutant dosage (e.g., $\sum c_h^{2.618}$ in Eq. 1)
- m_e = effective mean O_3 concentration (Eq. 2)
- P = percent effect (e.g., percent leaf injury)
- LI = leaf injury
- CR = crop yield reduction

The dependent variable is z and the natural logarithms of c and t are the independent variables used to calculate, by stepwise multiple linear regression, all of the following constant parameters:

- m_{gh} = geometric mean concentration; it is the concentration for a 1-h exposure duration calculated to cause 50% injury (Figure 1)
- m_{gt} = geometric mean concentration for an exposure time other than 1-h (Figures 1, 2)
- s_g = standard geometric deviation; it is the concentration calculated to cause 50% injury divided by the concentration calculated to cause 16% injury (Figure 1)
- v = the slope of regression lines with the same percent injury (injury isopleths) when plotted on logarithmic graph paper with a vertical concentration axis and a horizontal time axis (Figure 1); v was originally[1] called p

Estimating *v*, the Concentration-Time Slope

Acute[1,7] and acute-chronic[8] leaf injury data were fitted, in previous studies, with the L-H model:

$$c = m_{gh} s_g^z t^v \quad (3)$$

Eq. 3 can be formatted for multiple linear regression analyses by taking natural logarithms:

$$z = (-\ln m_{gh}/\ln s_g) + (1/\ln s_g)\ln c + (-v/\ln s_g)\ln t \quad (4)$$

The v parameter in Eq. 4 is related to exposure duration. At least two different exposure times are needed to calculate v. Only one exposure time was used in each set of NCLAN experiments conducted thus far. Therefore, v cannot be calculated from the NCLAN experiments. Instead, the v value used here will be the mean v, −0.376, calculated by regressing leaf injury, growth suppression, and leaf dry weight reduction data (Table I, column 10).

The example leaf injury data listed in Table I were read by the computer pro-

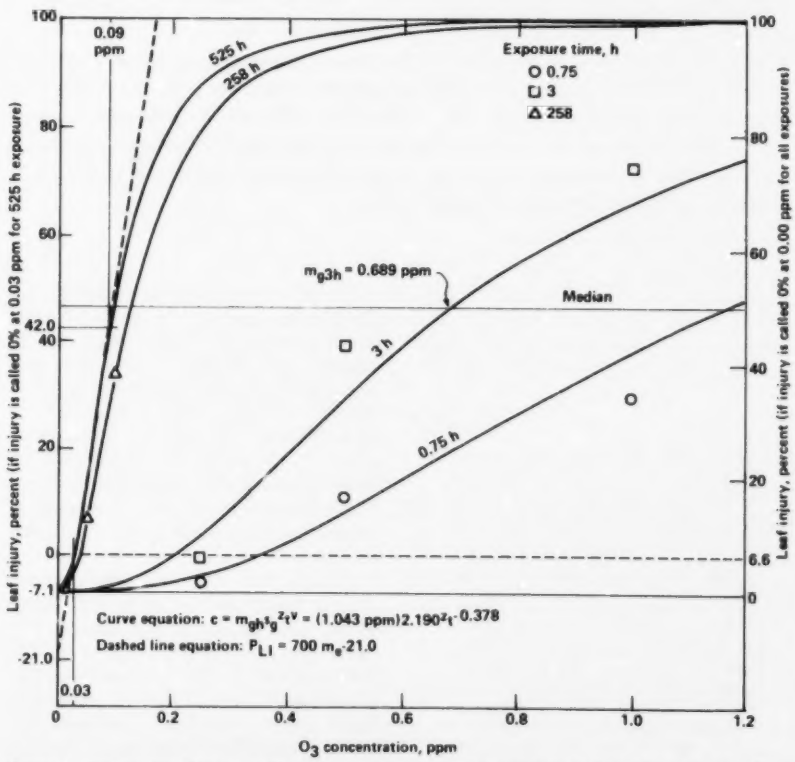

Figure 2. Percent leaf injury in Lee 68 and Dare soybeans exposed acutely (for 0.75 or 3 h) and Dare soybean exposed chronically (for 258 h or extrapolated to 525 h) to O_3 (Cartesian plot).

Table I. Observations and effect equation calculated parameters for plants exposed to O_3.

Plant (1)	Observations: Exposure duration, h[a] (2)	O_3 conc, ppm (3)	Effect, %[b] (4)	Number of deviations, z (5)	Data source references[c] (6)	Number of data points (7)	Effect equation calc parameters: m_{gh}, ppm (8)	s_g (9)	v (10)	Variance explained, % (11)
1.	Leaf injury in soybean exposed acutely & chronically to O_3					15	1.043	2.190	-.378	91.78
2.	Growth suppression in soybean exposed chronically to O_3					8	.789	1.875	-.354	80.38
3.	Leaf dry weight reduction in pinto bean exposed to O_3					8	.954	1.432	-.396	93.35
	Mean								-.376	
	.75	.25	1.75	-2.11	8,11					
	.75	.50	16.75	-.96	8,11					
	.75	1.00	34.14	-.41	8,11					
	1.50	.25	3.73	-1.78	8,11					
	1.50	.50	25.78	-.65	8,11					
	1.50	1.00	59.72	.25	8,11					
	3.00	.25	5.90	-1.56	8,11					
	3.00	.50	43.03	-.18	8,11					
	3.00	1.00	74.29	.65	8,11					
	120.00	.05	13.00	-1.13	12					
	120.00	.10	24.00	-.71	12					
	258.00	.05	13.00	-1.13	13					
	258.00	.10	38.00	-.31	13					
	552.00	.05	19.00	-.88	13					
	552.00	.10	37.00	-.33	13					
1.	Leaf injury in soybean exposed acutely & chronically to O_3					15	1.043	2.190	-.378	91.78

[a] Plant 1 was exposed 0.75–552 h. Plant 2 was exposed 120–798 h. Plant 3 was exposed 28–42 h.

[b] For acute leaf injury exposures, each percent effect listed above is the mean of three or four experimental runs at each combination of exposure duration and concentration. Using the mean prevents the greater number of individual acute observations from overshadowing the fewer number of chronic observations. As expected, this also reduces variance.

[c] Data source references are indicated here by superscript for plants 1,[8,11-13] 2,[12,13] and 3.[14]

gram that produced that table. The Gaussian transform (column 5) of percent leaf injury (column 4) was regressed against the natural logarithms of exposure duration (column 2) and O_3 concentration (column 3) to calculate the three parameters that describe the L-H model (columns 8–10). These parameters can be substituted into Eq. 3:

$$c = 1.043(2.190)^z t^{-0.378} \quad (5)$$

This equation was used to plot the leaf injury isopleths in Figure 1. The slope of these injury isopleths on this logarithmic plot is v, −0.378.

The correlation between measured (column 5) and modeled (Eq. 4) z values is 0.958. The square of this gives the percent variance explained (column 11). Thus, this model explains 92% of the variance of z and leaves only 8% unexplained.

Calculating Ambient Effective Mean O_3 Concentrations

Solving for the hour by hour expected cumulative effect of ambient pollutant concentrations is easier if time is linearized (has no exponent) and Eq. 4 is expressed instead as

$$z = -(\ln m_{gh})/(\ln s_g) - (v/\ln s_g)\ln(tc^{-1/v}) \quad (6)$$

Substitution of the Eq. 5 values gives

$$z = 0.482 \ln(tc^{2.65}) - 0.0537 \quad (7)$$

Impact, as defined previously,[8] is the time-concentration term, $tc^{-1/v}$, in Eq. 6. Impact is a form of air pollutant dosage. In this model equal impacts are expected to cause equal injuries.

Leaf injury was estimated previously by summing each hour's ambient impact for the daytime hours in a growing season to obtain the total impact (e.g., Eq. 1).[8] Total impact could be calculated instead by multiplying the total daytime hours of exposure by the average hourly impact. The effective mean concentration is defined in Eq. 2 as the average hourly impact raised to the $-v$ power:

$$m_e = [(\sum c_h^{-1/v})/n]^{-v}$$

where c_h is the hourly average O_3 concentration for each available daytime hour of data and n is the total number of such available hours of data in a growing season.

Eq. 6 can be revised by replacing c with m_e. Substitution of the Eq. 5 values then gives

$$z = 0.482 \ln(tm_e^{2.65}) - 0.0537 \quad (8)$$

where t is the total daytime exposure duration, whether ambient data are available for each daytime hour or not.

To study their separate effects, time and concentration were held constant during each leaf injury, growth suppression, or leaf dry weight reduction experiment referenced in Table I. However, ambient concentrations vary with time. The L-H model attempts to compensate for the expected variation in effects due to this variation in ambient concentrations by using the effective mean concentration. As noted above, this model assumes that equal total impacts cause equal injuries (Figure 1), whether the individual hourly impacts that add up to the total are caused by constant or by varying concentrations. Future studies could test this assumption.

If v equaled −1, the effective mean concentration would equal the arithmetic mean concentration. However, in this study the mean v of −0.376 (Table I, column 10) is far from −1. Thus, this model predicts that two sites with the same arithmetic mean O_3 concentration will have different effective means (and resultant injuries) if O_3 concentrations

Table II. Crop yield reduction parameters for plants exposed to O_3.

Plant Number (1)	Plant name (2)	Effect (3)	Crop yield reduction parameters[a] m_{gh}, ppm (4)	s_g (5)	v (6)	Days (7)
1	Corn, 2 cultivars	Crop yield reduction	1.672	1.552	-.376	75.0
2	Cotton, Acala SJ	Crop yield reduction	1.707	2.128	-.376	75.0
3	Kidney bean, California light red	Crop yield reduction	1.588	1.901	-.376	75.0
4	Lettuce, Empire	Crop yield reduction	1.138	1.879	-.376	75.0
5	Peanut, NC-6	Crop yield reduction	1.269	1.578	-.376	75.0
6	Soybean, 5 cultivars	Crop yield reduction	1.388	2.197	-.376	75.0
7	Wheat, 4 cultivars	Crop yield reduction	1.567	1.597	-.376	75.0

[a] Crop yield reduction parameters are from Table VI. An exposure of 75 days to ambient O_3 concentrations is used here for all crops for illustrative purposes.

vary a lot at one site and only a little at the other site. If concentrations at a site did not vary, then the effective mean would equal the arithmetic mean.

Effective mean O_3 concentrations (column 10 of Tables III, IV) were calculated for the summer daytime hours of years 1981–1983 for several (Table III) and all (Table IV) ambient air sampling sites for which O_3 data are available in the NADB for at least 50% of the desired hours in a year (column 3). (The example data in Table III were selected for later discussions here.) Variation in hourly ambient O_3 concentrations caused effective mean concentrations to average 15% higher (Table IV, column 15, last line) than arithmetic mean concentrations (column 9). This 15% increase in concentration increases leaf injury impact by 45% ($1.15^{-1/-0.378} = 1.45$, Eq. 6). (The 7-h effective mean concentration [column 10] is approximated quite well [column 14] by the mean of the daily 3-h maximum concentrations [column 8].)

Natural O_3 Concentrations

Forests and other natural sources emit hydrocarbons, and forest fires and other natural sources emit nitrogen oxides. Sunshine powers the photochemical reaction of these natural atmospheric constituents that produces some natural O_3. The NCLAN studies used a natural seasonal mean O_3 concentration estimate of 0.025 ppm. That is equivalent to an average effective mean O_3 concentration of 0.029 ppm [1.15(0.025 ppm) = 0.029 ppm], which rounds to 0.03 ppm. Sites in or near forests, such as sites in or near the Appalachian Mountains, with a larger concentration of natural sources, will probably have higher natural O_3 concentrations than will some other sites. For illustrative purposes only, though, the natural effective mean O_3 concentration assumed here will always be 0.030 ppm (Tables III, IV, heading over columns 16–22), approximately the same as some of the lower ambient concentrations (Table III) measured in states such as Florida, Maine, and Minnesota.

A Linear Approximation of the L-H Model

The NCLAN studies suggest,[9,10] for some crops exposed to usual ambient O_3 concentrations, that percent crop reduction is related linearly to the mean

Table III. Summer (June 1–August 31) 1981–1983 ambient 9:00 A.M.–4:00 P.M. O_3 parameters and estimated crop reductions, by site, for plants listed in Table II. (A conc exponent of $-1/-0.376$ is used to calculate the effective mean in column 10.)[a]

			Concentration, ppm, by averaging time						Effective mean divided by						Estimated crop reduc, %, (if 0% at .030 in col 10)						
	Pollut meas		2nd hi daily max.			Mean of daily max.			Effect mean	2nd hi max.		Mean of max									
Year	method[b]	% h avail	1 h	3 h	7 h	1 h	3 h	7 h	7 h	1 h	7 h	1 h	3 h	7 h	1 Cor	2 Cot	3 KBe	4 Let	5 Pnt	6 Soy	7 Whe
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
SITE 050580001I01, 200 E BUENA VISTA									BARSTOW					SAN BERNARDINO			(6700)		CA		
1981	14	97	.110	.107	.094	.074	.070	.064	.067	.61	.72	.91	.97	1.05	3	11	10	21	10	17	5
1983	14	90	.120	.110	.103	.088	.084	.079	.081	.68	.79	.93	.97	1.03	6	17	16	31	19	25	10
SITE 052680001I01, 14838 FOOTHILL BLVD									FONTANA					SAN BERNARDINO			(6700)		CA		
1981	14	100	.320	.290	.233	.208	.187	.145	.165	.51	.71	.79	.88	1.13	53	50	55	74	75	60	59
SITE 058480004I01, 304 TUOLUMNE ST. VALLEJO									VALLEJO					SOLANO CO			(7700)		CA		
1981	14	97	.090	.077	.064	.041	.037	.031	.037	.42	.58	.92	1.01	1.22	0	1	1	3	0	3	0
1982	14	98	.070	.063	.046	.034	.032	.028	.031	.44	.68	.91	.96	1.11	0	0	0	0	0	0	0
1983	14	99	.120	.093	.070	.038	.035	.029	.036	.30	.51	.95	1.03	1.23	0	1	1	2	0	2	0
SITE 100320002G02, MANATEE CO HEALTH DEPT 202 SIXTH AVE E									BRADENTON					MANATEE CO			(2540)		FL		
1981	11	91	.065	.050	.044	.026	.024	.020	.025	.38	.56	.96	1.04	1.21	0	-1	0	-1	0	-1	0
SITE 200260001F05, CARIBOU AIRPORT, 464 MAIN STREET, CARIBOU									CARIBOU					AROOSTOOK CO			(0045)		ME		
1981	14	91	.055	.054	.040	.025	.023	.021	.024	.43	.59	.96	1.02	1.15	0	-1	0	-1	0	-2	0
SITE 241840017F01, FERNBERG RD. 18 MILES NE OF ELY									LAKE CO					LAKE CO			(1840)		MN		
1982	14	97	.050	.050	.049	.028	.027	.024	.027	.54	.55	.96	1.00	1.12	0	0	0	-1	0	-1	0

[a] Selected example data are listed above. Similar data are available on request for one, several, or all (49 pages) states from the first author.

[b] Pollutant measurement method 11 uses chemiluminescence and method 14 uses an ultraviolet technique.

Table IV. Summer (June 1–August 31) 1981–1983 ambient 9:00 A.M.–4:00 P.M. mean O_3 parameters and estimated crop reductions, by state, for plants in Table II. (A conc exponent of −1/−0.376 is used to calculate the effective mean in column 10.)

State. (1)	Number of site-years (2)	% h avail (3)	Concentration, ppm, by averaging time: 2nd hi daily max. 1 h (4)	2nd hi daily max. 3 h (5)	2nd hi daily max. 7 h (6)	Mean of daily max. 1 h (7)	Mean of daily max. 3 h (8)	Mean of daily max. 7 h (9)	Effect mean 7 h (10)	Effective mean divided by: 2nd hi max. 1 h (11)	2nd hi max. 7 h (12)	Mean of max 1 h (13)	Mean of max 3 h (14)	Mean of max 7 h (15)	Estimated crop reduc, %, (if 0% at .030 in col 10): 1 Cor (16)	2 Cot (17)	3 KBe (18)	4 Let (19)	5 Pnt (20)	6 Soy (21)	7 Whe (22)
AL- 1	25	85	.108	.099	.089	.061	.058	.052	.057	.54	.65	.94	1.00	1.11	1	8	7	14	6	12	2
AK- 2	1	95	.041	.039	.037	.024	.022	.019	.022	.55	.60	.93	1.01	1.16	0	−1	0	−2	0	−2	0
AZ- 3	48	86	.099	.091	.075	.060	.056	.049	.053	.55	.72	.89	.95	1.08	1	6	5	12	4	10	2
AR- 4	6	95	.092	.090	.079	.060	.056	.049	.054	.58	.68	.90	.96	1.10	1	6	5	12	4	10	2
CA- 5	323	94	.136	.123	.100	.076	.070	.058	.066	.50	.66	.89	.96	1.14	7	12	12	21	14	17	8
CO- 6	32	90	.106	.095	.080	.066	.062	.055	.058	.56	.73	.88	.94	1.07	1	8	7	15	6	13	3
CT- 7	33	91	.172	.159	.126	.079	.074	.062	.074	.43	.59	.94	1.01	1.19	5	14	13	26	15	21	7
DE- 8	9	85	.131	.121	.096	.070	.065	.054	.063	.48	.65	.90	.97	1.17	3	10	9	19	9	15	4
DC- 9	6	89	.127	.119	.097	.066	.062	.051	.061	.48	.63	.94	1.00	1.20	2	9	8	17	8	14	4
FL-10	51	86	.089	.080	.066	.042	.039	.033	.039	.44	.59	.94	1.02	1.18	0	2	2	4	1	4	0
GA-11	12	82	.121	.112	.092	.062	.059	.050	.058	.49	.64	.94	1.00	1.17	2	8	7	15	7	13	3
HI-12	3	95	.032	.027	.024	.013	.012	.010	.013	.40	.52	1.00	1.11	1.27	0	−1	−1	−2	0	−3	0
IL-14	112	88	.107	.100	.085	.057	.054	.047	.053	.51	.63	.93	.99	1.13	1	6	5	11	4	10	2
IN-15	50	86	.114	.106	.092	.066	.062	.054	.060	.53	.65	.91	.97	1.12	2	9	7	16	7	14	3
IA-16	9	85	.076	.070	.060	.044	.041	.036	.040	.53	.67	.93	.98	1.13	0	2	2	4	1	4	0
KS-17	9	95	.094	.086	.075	.054	.051	.045	.050	.53	.67	.92	.97	1.10	0	5	4	9	3	8	1
KY-18	86	90	.100	.094	.077	.061	.057	.048	.054	.54	.70	.89	.95	1.13	1	6	5	12	4	10	2
LA-19	45	85	.108	.097	.080	.051	.046	.039	.048	.45	.60	.93	1.04	1.24	0	4	3	8	2	7	1
ME-20	19	87	.103	.093	.078	.048	.045	.040	.045	.44	.59	.95	1.01	1.14	0	3	3	7	2	6	1
MD-21	43	78	.137	.125	.103	.072	.068	.059	.068	.51	.66	.94	.99	1.14	3	12	11	22	11	18	5
MA-22	37	85	.123	.116	.098	.060	.057	.050	.057	.47	.59	.95	1.01	1.15	1	7	6	14	5	12	2
MI-23	31	90	.107	.099	.083	.055	.051	.042	.050	.47	.61	.91	.98	1.18	0	5	4	9	3	8	1
MN-24	23	88	.083	.076	.062	.045	.043	.037	.041	.50	.66	.91	.96	1.11	0	2	2	4	1	4	0
MS-25	8	91	.107	.100	.088	.058	.055	.050	.054	.52	.63	.94	.99	1.09	1	6	5	12	4	10	2
MO-26	29	87	.108	.100	.084	.053	.049	.042	.050	.46	.60	.94	1.01	1.19	1	5	4	10	3	8	1
MT-27	2	88	.073	.073	.068	.053	.052	.049	.051	.69	.74	.96	.98	1.04	1	5	5	10	4	9	2
NE-28	11	94	.067	.063	.055	.040	.037	.032	.036	.54	.66	.92	.97	1.14	0	1	1	3	1	3	0
NV-29	15	88	.100	.093	.083	.062	.059	.053	.057	.58	.70	.93	.98	1.08	1	7	6	14	5	12	2
NH-30	12	92	.094	.088	.077	.046	.043	.038	.044	.48	.57	.96	1.02	1.15	0	3	2	6	1	6	0
NJ-31	44	93	.147	.133	.112	.074	.069	.059	.069	.47	.62	.93	.99	1.17	3	12	11	22	11	18	5
NM-32	24	96	.092	.083	.069	.061	.058	.051	.053	.59	.78	.88	.93	1.05	1	6	5	11	4	10	1
NY-33	68	87	.110	.100	.082	.055	.051	.042	.050	.46	.61	.91	.99	1.20	1	5	4	10	4	8	1
NC-34	46	83	.098	.093	.081	.062	.059	.052	.057	.58	.70	.92	.97	1.09	1	7	6	14	6	12	3
ND-35	4	95	.065	.063	.059	.046	.045	.042	.044	.67	.75	.94	.97	1.04	0	3	2	6	2	5	0
OH-36	99	90	.113	.106	.088	.064	.060	.050	.057	.51	.65	.90	.96	1.16	1	7	6	14	6	12	2
OK-37	19	80	.102	.095	.082	.058	.055	.049	.054	.54	.66	.94	.99	1.10	1	6	5	12	5	10	2
OR-38	19	88	.092	.085	.065	.043	.040	.032	.039	.44	.61	.90	.96	1.22	0	2	2	4	1	3	0
PA-39	97	84	.118	.110	.088	.063	.059	.048	.057	.48	.64	.90	.96	1.18	1	7	6	14	5	12	2
PR-40	1	52	.025	.020	.019	.009	.008	.007	.010	.41	.54	1.09	1.28	1.45	0	−1	−1	−2	0	−3	0
RI-41	6	89	.126	.120	.103	.062	.058	.052	.059	.47	.58	.95	1.02	1.14	2	8	7	16	6	13	3
SC-42	19	87	.096	.090	.080	.059	.056	.049	.055	.57	.68	.93	.98	1.11	1	7	6	13	5	11	2
TN-44	24	87	.108	.100	.083	.063	.059	.050	.056	.52	.68	.89	.95	1.13	1	7	6	13	5	11	2
TX-45	77	78	.137	.123	.099	.061	.057	.048	.059	.44	.60	.96	1.04	1.22	2	8	7	15	7	13	3
UT-46	24	88	.115	.104	.085	.067	.063	.056	.060	.53	.71	.89	.95	1.07	1	8	7	16	6	13	3
VT-47	6	79	.079	.077	.068	.045	.043	.038	.043	.54	.63	.95	1.00	1.12	0	3	2	5	1	5	0
VA-48	46	90	.116	.110	.095	.070	.066	.058	.064	.55	.67	.92	.97	1.11	2	10	9	19	9	15	4
WA-49	27	93	.084	.079	.064	.039	.037	.030	.037	.46	.60	.95	1.02	1.23	0	2	1	3	1	3	0
WV-50	8	93	.111	.104	.085	.063	.059	.049	.057	.51	.67	.92	.99	1.19	2	8	7	14	6	12	3
WI-51	76	88	.106	.099	.086	.055	.052	.047	.053	.51	.62	.96	1.01	1.13	1	6	5	11	4	10	2
Mean	1824	88	.115	.106	.088	.062	.058	.050	.057	.50	.65	.92	.98	1.15	2	8	7	14	7	12	3

O_3 concentration. How well does the L-H lognormal model agree with such a linear relationship? Also, a statistical table or a hand-held or other programmable calculator or computer is needed to use the L-H model. Could a simpler linear approximation of the L-H model often be used instead? One purpose of this section is to explore these two questions.

To illustrate how the shape of the L-H model changes as exposure duration increases, leaf injury data (from Table I) are displayed and modeled on a Cartesian plot (Figure 2). Figure 2 is also used to illustrate a method for estimating the percentage of leaf injury (and later, crop reduction) if leaf injury is called 0% at the assumed natural effective mean O_3 concentration of 0.03 ppm.

Let us assume that soybean is exposed for 525 h (75 days for 7 h/day, 9:00 A.M.–4:00 P.M.) to various ambient effective mean O_3 concentrations (Figure 2, bottom axis, left curve). The L-H model (Eq. 5) predicts the percent leaf injury stated on the right axis, if compared with a natural O_3 concentration of 0.00 ppm, or the percent stated on the left axis, if compared with a natural O_3 concentration of 0.03 ppm.

Except for the Los Angeles area, most

Table V. Observations and calculated crop yield reduction parameters for plants exposed to O_3.

Plant (1)	Observations: Effective mean O_3 conc, ppm (2)	Yield, g (3)	Yield reduction, % (4)	Number of deviations, z (5)	Data source reference (6)	Number of data points (7)	Yield reduction parameters: m_{gt}, ppm (8)	s_g (9)	Variance explained, % (10)
	.025	20.40	1.79000	-2.10	9				
	.048	18.40	11.41843	-1.20	9				
	.070	14.90	28.26819	-.57	9				
	.095	11.70	43.67368	-.16	9				
	.121	9.40	54.74637	.12	9				
6.1	Soybean, Corsoy					5	.1082	2.009	99.79
	.035	4.95	.00071	-4.34	15				
	.069	4.91	.80878	-2.41	15				
	.109	4.43	10.50569	-1.25	15				
	.139	3.30	33.33381	-.43	15				
7.3	Wheat, Holly					4	.1654	1.430	99.86

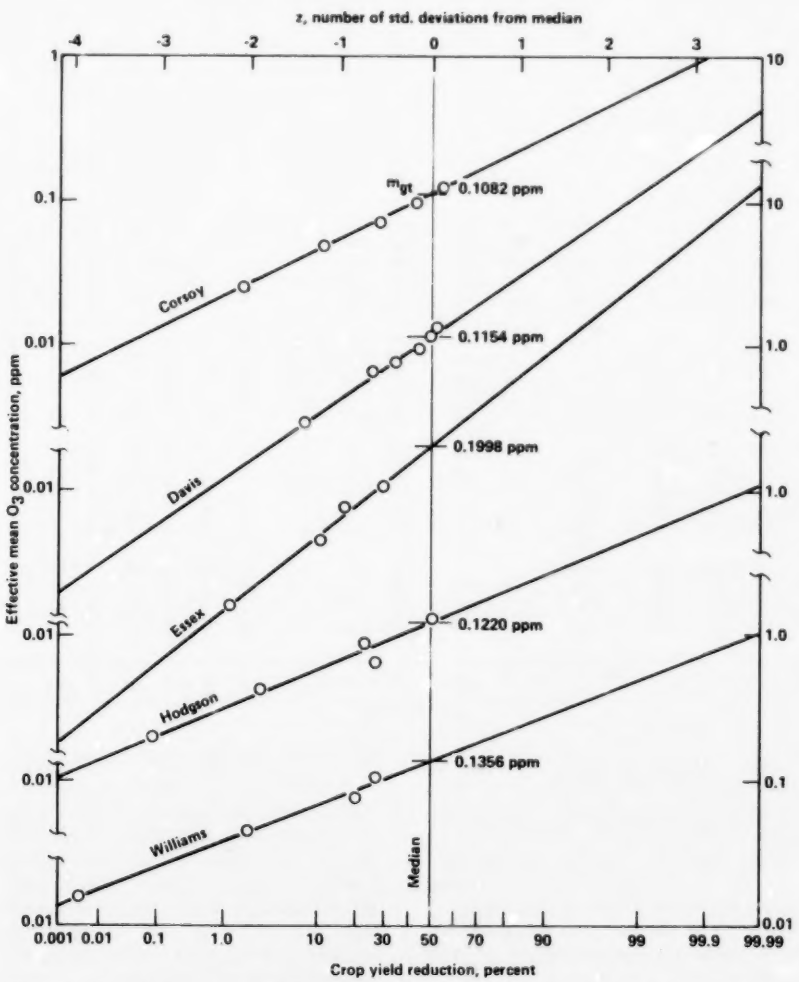

Figure 3. Percent crop reduction for five soybean cultivars exposed to O_3 as stated in Table VI.

effective mean O_3 concentrations (Table IV) are in the 0.03–0.09 ppm range. The 525-h curve in Figure 2 is substantially linear in this range. By definition, 0% injury occurs at 0.03 ppm. Leaf injury calculates as 42.0% at 0.09 ppm. The dashed line drawn through these two points can be expressed as

$$P_{LI} = 700\, m_e - 21.0 \qquad (9)$$

Leaf injuries calculated with this linear equation are within 1% of those calculated with Eq. 7 (for the 0.03–0.09 ppm range).

Crop Yield Reduction Studies

Crop yield weight (Table V, column 3) is shown for two example crops exposed to various effective mean O_3 concentrations (column 2) for various numbers of days (Table VI, column 6) in outdoor, open-top chambers.[15,16] These crops were exposed either to carbon-filtered (CF) air or to nonfiltered (NF) air to which a constant concentration of O_3 was added (NF-1, NF-2, or NF-3). O_3 was added for 7 h/day (usually 9:00 A.M.–4:00 P.M.) on nonrainy days. Only enough O_3 was added to each NF-1 chamber to replace the O_3 lost by ducting ambient air into the chamber.

An effective mean O_3 concentration (Table V, column 2) could be calculated for each experimental crop exposure if the O_3 concentration for each hour composing that exposure were readily available in a computer file (in order to calculate a frequency distribution of these hourly concentrations). Since such a file is not readily available, effective mean O_3 concentrations will be estimated, as described below.

Ambient effective mean O_3 concentrations (Table IV, column 10) average 1.15 (column 15, last line) times arithmetic mean O_3 concentrations (column 9), and thus average 0.15 greater than the arithmetic means. Therefore, CF and NF-1 mean O_3 concentrations were increased by this 0.15 factor and listed in column 2 as the estimated effective mean O_3 concentrations. Experimental concentrations higher than NF-1 were achieved by adding a constant incremental concentration of O_3 to each exposure chamber. Therefore, these experimental concentrations did not vary with time as much as those measured at most ambient air monitoring sites. Effective means for these higher exposures were estimated by multiplying 0.15 times the NF-1 concentration and adding this to these higher concentrations.

Regression Analyses

Yield reduction z values (Table V, column 5) were regressed against the natural logarithms of effective mean O_3 concentrations (column 2) to calculate the geometric mean (column 8) and standard geometric deviation (column 9) that describe each data set.

Since crop loss will be calculated here as crop loss above a natural effective mean O_3 concentration, the only effect the technique described below will have is to improve the fit of crop reduction experimental data to the L-H model (Figure 3). The highest weight yield in each data set was assigned (by this technique) the percent yield reduction that explained the greatest percentage of variance (column 10). That assignment was determined by trial and error by first setting the highest weight yield (column 3) to an arbitrary percent yield reduction (column 4) of 0.01% and calculating the percent variance explained for the data set. That yield reduction was then increased to 0.02% and variance explanation for the data set was recalculated. If more variance was explained at 0.02% than at 0.01%, then yield reduction was increased another 0.01% and variance was recalculated. Variance was recalculated repeatedly in this manner until variance explanation first began to decrease. The yield reduction at that point was then selected and listed in Table V (e.g., Corsoy soybean; the most variance was explained when the highest weight yield was set at a yield reduction of 1.79%).

If variance explanation was less when the highest yield was set at a 0.02% yield reduction than at 0.01% yield reduction, then yield reduction for the highest weight yield was reset to 0.00001% and increased repeatedly by 0.00001% until variance explanation first began to decrease. The yield reduction at that point was then selected and listed in Table V (e.g., Holly wheat; the most variance was explained when the highest weight yield was set at a yield reduction of 0.00071%).

The FORTRAN computer program that produced Table V is available from the first author. For small numbers of data sets, the same approach may easily be applied graphically by trial and error (Figure 8 in Ref. 8).

The calculated regression lines explain more than 99.0% of the variance of z for 60% (9 of 15) of the cultivars studied (Table VI, column 9). This excellent fit is largely because the three descriptive parameters (the geometric mean, the standard geometric deviation, and the assignment of the yield reduction for the sample with the highest yield) leave only one to three degrees of freedom for each data set.

Calculating 1 h Geometric Mean Concentrations

The L-H model is a lognormal model. It uses the logarithms of O_3 concentration and exposure time. The logarithm of 1 h is zero, the origin on a logarithmic scale. Therefore, one parameter of the L-H model (Eq. 3) is the 1-h geometric mean, m_{gh}. This parameter has physical significance when used for acute leaf injury. It is the 1-h exposure concentration expected to cause 50% leaf injury. It is also the correct L-H parameter to use here to model crop reduction data, but does not have physical significance because a single 1-h exposure duration is not a realistic crop reduction exposure. When the t variable and m_{gh} are used together (Figure 1), then realistic ambient crop reduction estimates result.

The method used to produce Table V was used to calculate geometric means and standard geometric deviations (Table VI, columns 10 and 12) for all the

Table VI. Exposure data and calculated crop yield reduction parameters for crops exposed to O_3 in outdoor, open-top chambers.

	Crop (1)	Ref (2)	State where exposed (3)	Time from planting to harvesting, days (4)	O_3 exposure: Date began (5)	O_3 exposure: Duration, Days (6)	O_3 exposure: Duration, h (7)	Number of data points (8)	Variance explained, % (9)	Geometric mean, ppm: m_{gt} (10)	Geometric mean, ppm: m_{gh} (11)	s_g (12)
1.1	Corn, PAG-397	10	IL	130	6/20/81	83	581	5	96.42	0.1526	1.671	1.561
1.2	Corn, Pioneer	10	IL	130	6/20/81	83	581	6	93.82	0.1529	1.674	1.543
1	Corn, geometric mean										1.672	1.552
2	Cotton, Acala SJ	10	CA	189	7/ 6/81	72	504	6	98.36	0.1645	1.707	2.128
3	Kidney bean, Calif. lt. red	9	NY	119	8/20/80	22	154	5	98.74	0.2390	1.588	1.901
4	Lettuce, Empire	9	CA	83	9/ 1/80	74	518	6	99.64	0.1085	1.138	1.879
5	Peanut, NC-6	9	NC	138	6/16/80	113	791	5	99.80	0.1032	1.269	1.578
6.1	Soybean, Corsoy	9	IL	112	8/ 6/80	65	455	5	99.79	0.1082	1.081	2.009
6.2	Soybean, Davis	10	NC	144	6/24/81	111	777	6	99.17	0.1154	1.409	2.654
6.3	Soybean, Essex	10	MD	140	7/20/81	65	455	4	98.45	0.1998	1.995	3.087
6.4	Soybean, Hodgson	10	NY	127	7/23/81	70	490	5	95.92	0.1220	1.253	1.807
6.5	Soybean, Williams	10	MD	118	7/20/81	65	455	4	99.59	0.1356	1.354	1.722
6	Soybean, geometric mean										1.388	2.197
7.1	Wheat, Blueboy II	15	NC	219	4/ 9/77	54	378	4	100.00	0.1712	1.595	1.538
7.2	Wheat, Coker 47-27	15	NC	219	4/ 9/77	54	378	4	99.54	0.1603	1.493	1.985
7.3	Wheat, Holly	15	NC	219	4/ 9/77	54	378	4	99.86	0.1654	1.541	1.430
7.4	Wheat, Oasis	15	NC	219	4/ 9/77	54	378	4	99.93	0.1763	1.642	1.491
7	Wheat, geometric mean										1.567	1.597

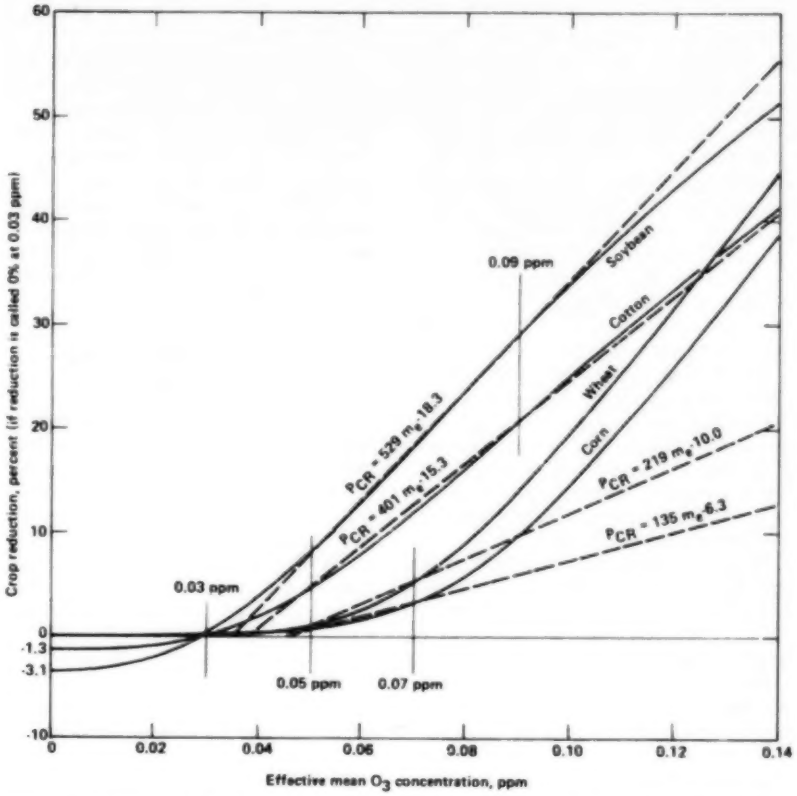

Figure 4. Percent crop reduction estimated for crops exposed to various effective mean O_3 concentrations for 75 days (for 7 h/day, totalling 525 h).

crop reduction data analyzed here. Crops were exposed for 7 h/day for various numbers of days (column 6), resulting in various total hours of exposure (column 7).

Figure 1 indicates that the 1-h to other-h geometric mean interrelation is

$$m_{gt} = m_{gh}t^{v} \qquad (10)$$

Solving for the 1-h geometric mean,

$$m_{gh} = m_{gt}t^{-v} \qquad (11)$$

Using the mean v of −0.376 (Table I),

$$m_{gh} = m_{gt}t^{0.376} \qquad (12)$$

This equation was used to calculate all the 1-h geometric means (Table VI, column 11).

Calculating Composite Geometric Means and Deviations

Percent crop reductions and calculated regression lines are shown for five soybean cultivars on a log-probability plot (Figure 3). Since the same concentration-time slope, v, is used here for all crop reduction analyses, parameters for all of the cultivars for one species can be compared at any single duration (e.g., Figure 1). As noted above, since the logarithm of 1 h is zero, the most convenient single parameter to use is one with a 1-h duration, the 1-h geometric mean, m_{gh}.

The L-H model uses the logarithm of concentration. Therefore, the best average 1-h geometric mean for these five soybean cultivars should probably be a logarithmic mean. The geometric mean of the five 1-h geometric means is a logarithmic mean and is used here:

$$m_{ghc} = \exp[(\sum \ln m_{gh})/n] \qquad (13)$$

where exp indicates that e, 2.718, is raised to the power in brackets.

The mean slope of the five lines on Figure 3 may be the best composite representation of such slope data. The slope of each line is the natural logarithm of its standard geometric deviation. Therefore,

$$s_{gc} = \exp[(\sum \ln s_g)/n] \qquad (14)$$

A species composite 1-h geometric mean and composite standard geometric deviation were listed for the five soybean cultivars (Table VI). Similarly, composite parameters were calculated and listed for the two corn cultivars and the four wheat cultivars. In order to display expected crop reductions calculated with these three sets of composite parameters, these parameters were used to plot Figure 4. A plot for Acala SJ cotton is also shown.

Table VII. Estimated crop yield reduction in years 1981–1983 due to O_3 for the five most valuable U.S. crops.

Crop (1)	Estimated yield reduction due to O_3, % (2)	1982 crop value, $ billions (3)
Corn	2	19.4
Soybean	12	12.5
Hay	3	9.6
Wheat	3	9.5
Cotton	8	3.4
Total	(5)	54.4

Linear Approximations of Crop Reduction Curves

As mentioned earlier, a statistical table or a programmable handheld or other calculator or computer is needed to use the L-H model. A linear approximation of the L-H model would be easier to use, especially for approximate calculations. The crop reduction curves for soybean and cotton are almost linear for the ambient effective mean O_3 concentrations measured at most sites (excluding the Los Angeles area) and can be approximated by the linear equations shown in Figure 4, which were calculated using the two points on each curve that intersect concentrations of 0.05 and 0.09 ppm. The wheat and corn plots are very curved in the ambient range. They still can be approximated within about 1% for most ambient sites by using the linear equations shown, which were calculated using the two points on each curve that intersect concentrations of 0.05 and 0.07 ppm.

Estimating County Average Percent Crop Loss

County-average effective mean O_3 concentrations are indicated by shading in Figure 5. Figures 4 and 5 can be used to estimate average crop reductions. For example, shading indicates a 0.06 ppm average effective mean O_3 concentration for most Indiana counties for which NADB data are available. The soybean equation in Figure 4 can be used to estimate that a 13% average crop yield reduction for soybean is expected for these counties.

Estimating National Average Percent Crop Loss

Average estimated crop losses for all NADB O_3 sites (Table IV, last line, columns 16–22) will be used here (Table VII, column 2) to estimate an overall national average crop loss. This loss will be weighted by the dollar value[17] (column 3) of the five largest dollar volume crops harvested in 1982: corn, soybean,

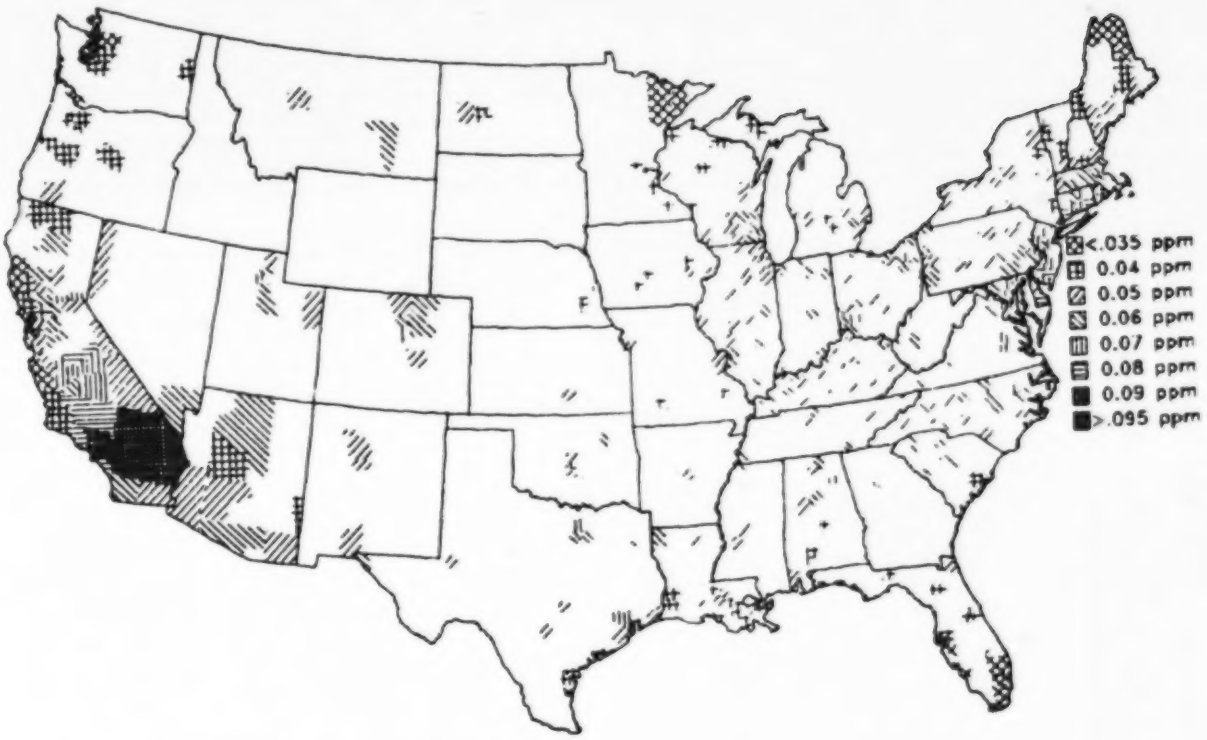

Figure 5. County-average effective mean O_3 concentrations, 1981–1983.

hay, wheat, and cotton. A national average crop reduction is available (Table IV, last line) for each of these except hay. The wheat reduction average is used here for hay. When yield reductions (column 2) are weighted by dollar volumes (column 3), the national average for all crop loss due to ambient O_3 is estimated (column 2) to be 5%.

A Comparison of the Weibull and Lognormal Models

Both the Weibull and the lognormal models can estimate crop reduction as a function of O_3 concentration. These two models complement and reinforce each other. They both have their strong points. Some of their strengths will be discussed here. A comprehensive analysis of crop reduction data might use both models.

Both models produce similar curves (Figure 6). Each point plotted in Figure 6 is the treatment mean crop reduction for four individual outdoor exposure chambers. Both models operate easily on these means. The Weibull model also easily used each of the four individual chamber values represented by each single plotted point to calculate the curve plotted.[10] The lognormal model does not work well when each of the four individual chamber values are used instead of their mean. The lowest percent crop reduction value in a data set must be set higher than zero because the Gaussian transform cannot use negative numbers (Table V, column 4). This procedure results in a poor fit of the detailed data set to the L-H model. The Weibull model is not limited in this way. It can use negative percent crop reduction values (Weibull equation in Figure 6). This capability enables the Weibull model to represent the detailed data set well and to be used in many statistical tests. A test for homogeneity, for instance, showed that data from several cultivars could be combined to calculate species parameters.[10]

One inherent characteristic of the L-H model is that it defines an effective mean concentration, a parameter that attempts to consider the effect of high and low hour by hour ambient O_3 concentrations. A related characteristic is

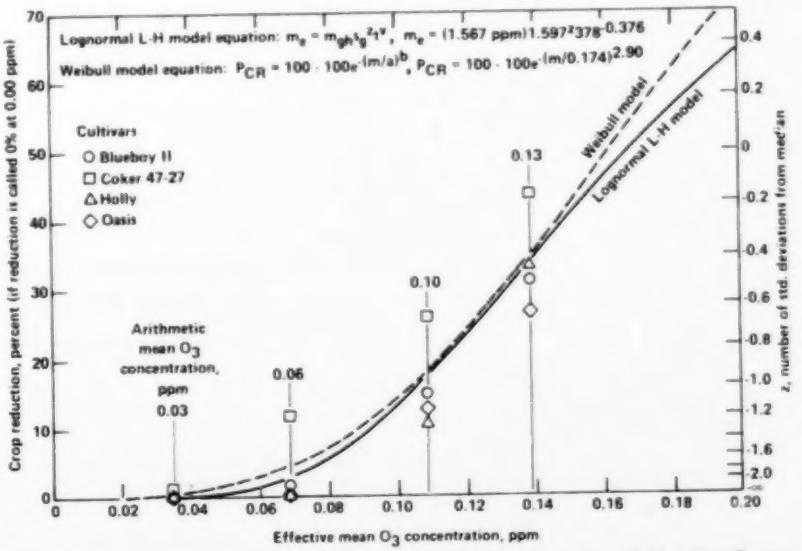
Lognormal L-H model equation: $m_e = m_{gh}{}^{s_g{}^{z_1 v}}$, m_e = (1.567 ppm)$^{1.597^{z}378^{-0.376}}$
Weibull model equation: $P_{CR} = 100 \cdot 100e^{-(m/a)^b}$, $P_{CR} = 100 \cdot 100e^{-(m/0.174)^{2.90}}$
Cultivars
Blueboy II
Coker 47-27
Holly
Oasis
Weibull model
Lognormal L-H model
Arithmetic mean O_3 concentration, ppm
0.03
0.06
0.10
0.13
Crop reduction, percent (if reduction is called 0% at 0.00 ppm)
z, number of std. deviations from median
Effective mean O_3 concentration, ppm

Figure 6. Percent crop reduction for four cultivars of wheat exposed to various effective mean O_3 concentrations for 54 days (for 7 h/day, totalling 378 h).

that the L-H model has a time variable. Some soybean cultivars were exposed for 71% longer than others (Table VI). This difference is adjusted in the L-H model. Also, the time variable in the L-H model can be used to estimate crop reductions for exposure durations that differ from the durations used in the crop experiments.

Estimating Crop Reduction as a Function of O_3 Concentration Parameters

Estimated soybean crop reduction (Table III, column 21), for all 1824 site-years of 1981–1983 data in the NADB, was plotted and regressed as a function of daytime arithmetic mean O_3 concentration (column 9 and Figure 7) and the second highest daily maximum hour O_3 concentration (column 4 and Figure 8). The numbers of resulting site-years at the various coordinates are listed in each

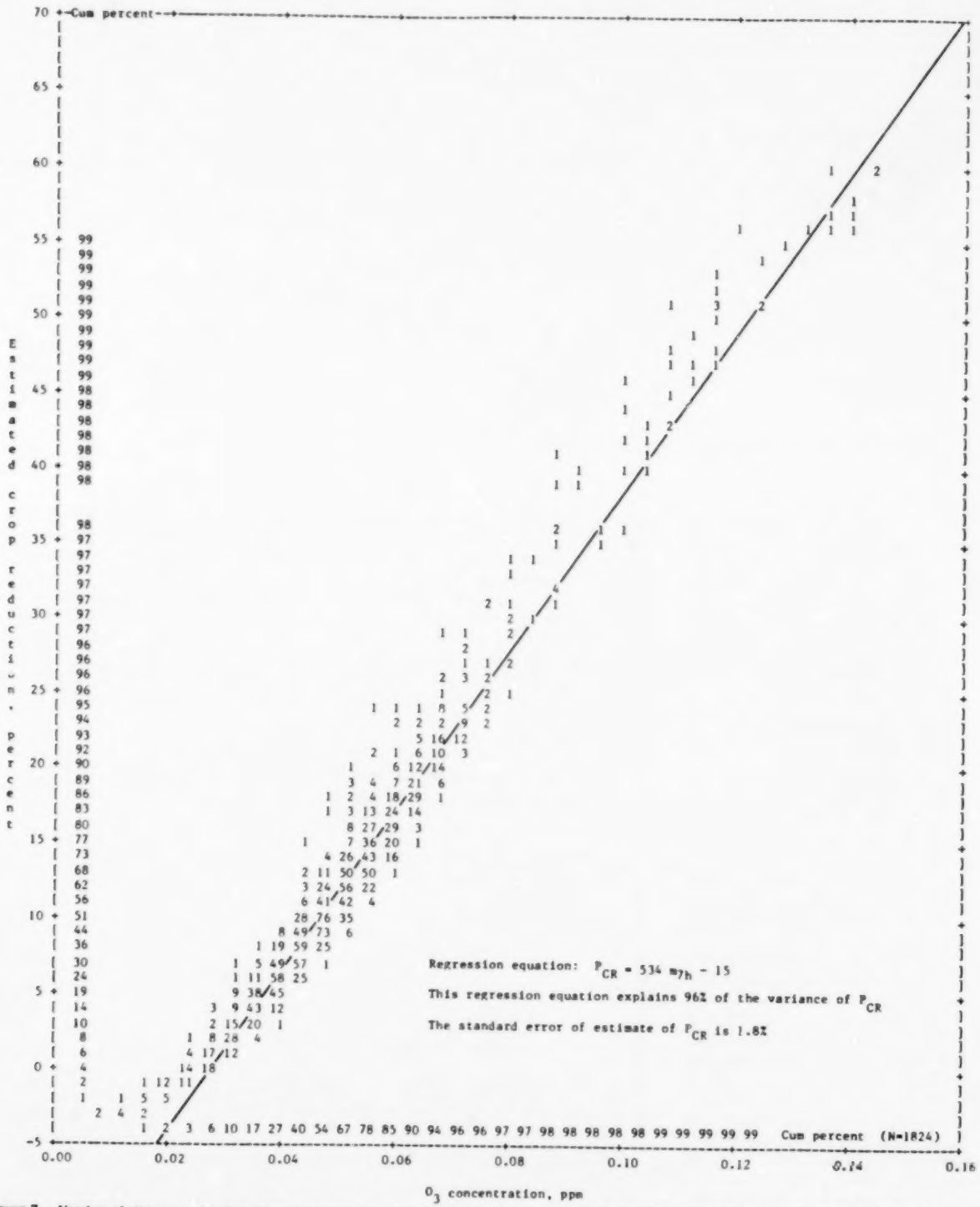
Cum percent
Estimated crop reduction, percent
Regression equation: $P_{CR} = 534\ m_{7h} - 15$
This regression equation explains 96% of the variance of P_{CR}
The standard error of estimate of P_{CR} is 1.8%
Cum percent (N=1824)
O_3 concentration, ppm

Figure 7. Number of site-years at estimated soybean percent crop reduction vs. 9:00 A.M.–4:00 P.M. mean O_3 concentration measured at NADB sites from June 1–August 31 of each year from 1981 to 1983.

(bivariate frequency distribution) scatter plot.

The equations of the regression lines in Figures 7 and 8 are

$$P_{CR} = 534\, m_{7h} - 15 \qquad (15)$$

$$P_{CR} = 187\, c_{2hi\,h} - 10 \qquad (16)$$

The variances in percent crop reduction explained by the two regression lines are 96% and 81%, respectively. Thus, the second plot leaves about five times as much variance unexplained as does the first plot. The standard errors of estimate about the lines are 1.8% and 3.8% crop reduction (i.e., 68% of the data points in these two figures lie within these distances from these two regression lines).

A third scatter plot could show estimated soybean crop reduction plotted versus the effective mean O_3 concentration (Table III, column 10). This plot would be almost identical to the plot for

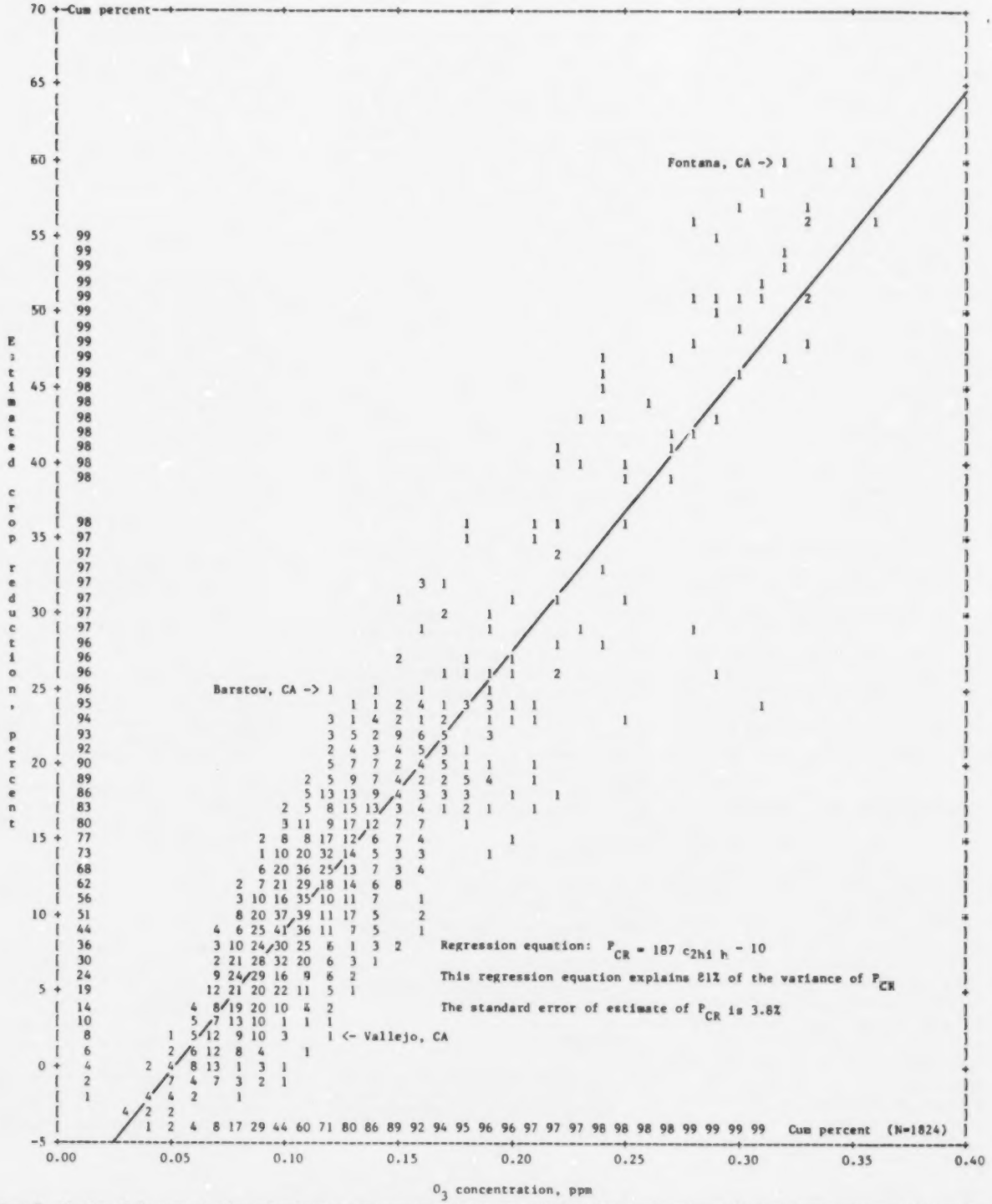

Figure 8. Number of site-years at estimated soybean percent crop reduction vs. second highest daily maximum hourly O_3 concentration measured at NADB sites from 9:00 A.M.–4:00 P.M. of June 1–August 31 of each year from 1981 to 1983.

soybean in Figure 4, since crop reduction was estimated directly from the effective mean O_3 concentration. Such a third plot would of course predict that the closest interrelation between "cause" and "effect" would be achieved if the effective mean O_3 concentration were used as the NAAQS parameter to reduce crop reduction to a specified level.

Comparisons with an O_3 Standard

The O_3 NAAQS[18] specifies that the "expected number of days per calendar year" that the 1-h average O_3 concentration can exceed 0.12 ppm must be "equal to or less than 1." This is approximately the same as stating that if several years of data are available for an ambient air sampling site and the highest hour concentration is available for each day, then on the average, the second highest of these values in a calendar year shall not exceed 0.12 ppm.

The annual second highest daily maximum hour O_3 concentration measured in the U.S. for the summer daytime hours of years 1981–1983 averaged 0.115 ppm (Table IV, last line, column 4), which rounds to 0.12 ppm, equal to the O_3 standard. The average soybean crop yield reduction estimate is 12% (column 21). This 12% reduction is associated with an effective mean O_3 concentration of 0.057 ppm (column 10) and an arithmetic mean of 0.050 ppm (column 9).

The vertical spread of points about the regression line is much greater in Figure 8 than in Figure 7. For the average site that exactly achieves the O_3 standard of 0.12 ppm (for summer daytime hours), estimated soybean crop reduction varies from 2% (in Vallejo, CA, Table III) to 25% (in Barstow, CA). The bottom line of Figure 8 indicates that 71% of the sites have a second highest hour concentration of 0.125 ppm or less.

Assumptions and Future Research

Crop reduction estimates in this paper are based on experiments and assumptions. Future research could improve or replace some of these assumptions. A reiteration here of some of the assumptions may suggest potential fruitful future research projects.

Both the Weibull and the lognormal models would probably give similar total national average crop loss estimates (Figure 6). The υ parameter used in the lognormal L-H model (to calculate the effective mean O_3 concentration, Eq. 2) is important for estimating the relative effect of O_3 concentration variation with time, from site to site, and for estimating crop losses for exposure durations that differ from those used in the crop loss experiments. Future studies of υ values could improve these two types of estimates.

The lognormal L-H model assumes that equal effective mean O_3 concentrations cause equal injuries, whether the effective mean is a result of constant or of varying ambient O_3 concentrations. This assumption could be tested in future experimental exposures of plants.

The υ values calculated here are based on leaf injury, growth suppression, and leaf dry weight reduction studies and are assumed to hold also for crop yield reduction. Crop yield reduction studies could be designed to calculate υ values and to compare them with υ values obtained for these other types of injuries.

Effective mean O_3 concentrations for crop reduction experiments were estimated from ratios rather than calculated from hourly measurements. Hourly concentration data for these types of experiments could be stored in a computer file format similar to that used in the NADB. The same computer programs could then be used to calculate effective mean concentrations for both experimental crop exposures and for ambient sampling sites.

The value assumed for the natural effective mean O_3 concentration (0.03 ppm was always used here) will probably affect results very little for crops like wheat and corn but will be quite important for crops like soybean and cotton (Figure 4). Any natural effective mean O_3 concentration from 0.00 to 0.04 ppm will give essentially the same percent crop reduction estimates for wheat and corn. For soybean and cotton, any natural effective mean O_3 concentration above 0.02 ppm will affect calculated crop reductions. Future studies that improve the accuracy of the natural effective mean O_3 concentration could improve crop reduction estimates for these two crops and for others with similar "sensitivity thresholds."

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